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SPECTROSCOPY OF LOW ENERGY NEUTRINOS FROM THE SUN

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ABSTRACT

Two methods are discussed for the solar neutrino spectroscopy in the sub-MeV region: absorption in a loaded liquid scintillator and elastic scattering in a TPC. The different neutrino oscillation solutions predict a strong effect in this energy region where the largest fraction ($\sim 98\%$) of solar neutrinos lies. Both projects have reached the stage where they have to prove their capability to attain a background low enough for solar neutrino detection.

1. Introduction

The largest fraction of the calculated standard model solar neutrino flux lies below 1 MeV^1 . In particular the pp neutrinos are the most abundant source of solar neutrinos (about 91% of the total flux) and they are calculated to 1% accuracy, whereas the ${}^7\text{Be}$ neutrinos give a contribution of about 7% to the total flux and they are calculated to 10% uncertainty.

The different neutrino oscillation solutions predict a strong influence on the low energy ν_e from the Sun²). A measurement of the solar neutrino spectrum in the sub-MeV region might be the only possibility of having a precise determination of the mass difference and the mixing angle relevant to the solar neutrino phenomena. This is particularly true if Kamland, the long-baseline reactor experiment, will not see anti-neutrino oscillations in the δm^2 region down to $\sim 10^{-5} \text{ eV}^2$. At the same time the measurement of the pp neutrinos would be an important test of the stellar evolution theory.

All the running experiments sensitive to the sub-MeV neutrinos from the Sun are radiochemical (Homestake, Gallex/GNO, Sage) and cannot do any neutrino spectroscopy. BOREXINO will start taking data next year and it is so far the only real time experiment which can detect low energy neutrinos by measuring the energy of the recoiling electron in the reaction $\nu_e + e^- \rightarrow \nu_e + e^-$. The 250 keV threshold on the electron kinetic energy allows only the detection of the ${}^7\text{Be}$ neutrinos.

In this paper I will describe two different approaches which are studied for the spectroscopy of both the pp and ${}^7\text{Be}$ neutrinos. First I will discuss the neutrino detection through the $\nu_e + (A, Z) \rightarrow (A, Z + 1)^* + e^-$ interaction in a liquid scintillator detector and then, in a more detailed way, the detection through the $\nu_e + e^- \rightarrow \nu_e + e^-$ elastic scattering in a gas filled Time Projection Chamber.

2. Loaded liquid scintillator: LENS

In 1997 R.Raghavan proposed³⁾ to detect the low energy ν_e from the Sun through the charged current interaction $\nu_e + {}^{176}\text{Yb} \rightarrow {}^{176}\text{Lu}^* + e^-$. The neutrino energy is simply given by the sum of the electron kinetic energy and of the Q value of the reaction (301 keV). The delayed coincidence between the electron from the ν_e interaction and the gamma ray from the de-excitation of ${}^{176}\text{Lu}^*$ ($E_\gamma = 71.5 keV$, $\tau = 50 ns$) gives the ν_e tag. In addition ${}^{176}\text{Yb}$ has a reasonable isotopic abundance (12.8%) and it is a stable nucleus against single β decay (it is an even-even $\beta\beta$ candidate nucleus).

Since the proposal of Raghavan a strong research program has been undertaken by the LENS Collaboration to develop a liquid scintillator with high and stable light yield at high Yb content. An important technical success has been achieved at the beginning of this year with the production of an aromatic scintillation solvent loaded with organo-metallic Yb compounds with the following features⁴⁾: light yield of 8400 photons/ MeV with 10% Yb loading, attenuation length of a few meters and stability in time during about 1 year. A modular detector could be filled with this scintillator to have, with 20 *tons* of Ytterbium, a rate of 180 *pp* and 143 ${}^7\text{Be}$ events/year.

The background studies give a less promising perspective. It is true that, thanks to the coincidence, it is possible to release the requirements on the contaminants which give random coincidences of uncorrelated background (by about 6 orders of magnitude as compared to BOREXINO), however severe sources of correlated background have been identified. For correlated background we mean all the decay schemes which give two signals correlated in time and space as the ν_e tag, such as ${}^{231}\text{Th}$ (${}^{235}\text{U}$ chain), ${}^{169}\text{Yb}$ (from n capture on ${}^{168}\text{Yb}$), ${}^{176}\text{Lu}$ (a rare earth difficult to remove from Ytterbium).

Shortly, the technical problems related to the production of the Yb loaded scintillator seem to be solved, but the possibility of reaching an acceptable background has still to be demonstrated. This is one of the main items for the LENS low background facility which is almost ready in the Gran Sasso underground laboratory.

This spring Raghavan succeeded in producing an Indium loaded liquid scintillator⁵⁾, using the same recipe as for Ytterbium and obtaining similar results. Since 25 years ${}^{115}\text{In}$ is the dream of the physicists aiming at the low energy solar neutrino detection. The detection scheme is the following: $\nu_e + {}^{115}\text{In} \rightarrow {}^{115}\text{Sn}^* + e^-$. The de-excitation of ${}^{115}\text{Sn}^*$ ($\tau=4.76 \mu s$) gives rise to a 115.6 keV electron (or γ in 4% of the decays) and to a 497.3 keV γ .

Indium is so appealing as a neutrino detector medium for the following reasons: low Q value (118 keV), delayed coincidence with strong signature and of relatively high total energy (613 keV), high isotopic abundance (95.7%).

The most serious problem, which till now prevented the use of Indium as a neutrino

detector medium, is the beta decay of ^{115}In itself ($\tau = 6 \cdot 10^{14}$ years, end-point energy=495 *keV*, activity: 0.25 *Bq/gr*). The relatively high light output of the new scintillator might give an energy resolution good enough to efficiently distinguish the $^{115}\text{Sn}^*$ de-excitation (which is the delayed coincidence to tag the ν_e interaction) from the beta decay with the emission of a Bremsstrahlung photon of ^{115}In (this is the most severe background source due to the Indium radioactivity⁵⁾). As a matter of fact, the former event has a total energy of 613 *keV* whereas the latter one can have, at most, a 495 *keV* energy. In addition to energy resolution, the granularity is the other key feature required by an Indium detector to fully exploit the strong signature of the ν_e absorption. Both the points are now studied to check if a background could be achieved low enough for solar neutrino detection.

3. Solar TPC

The great advantage of detecting the solar neutrinos by measuring both the energy and the direction of the recoiling electron in the $\nu + e^- \rightarrow \nu + e^-$ elastic scattering is shown by the Kamiokande and SuperKamiokande experiments with the high energy ^8B neutrinos. As a matter of fact, the water Čerenkov detectors would have not been able to identify any solar neutrino signal without the reconstruction of the electron direction. Actually also the μ and τ neutrinos scatter electrons, but with a lower cross section (1/7-1/6 of the ν_e one).

The measurement of both the electron energy and direction allows for:

- the solar neutrino astronomy, with an unambiguous signal identification,
- the spectroscopy of the neutrinos from the Sun (the ν_e energy is reconstructed from the electron energy and direction),
- the on-line measurement of the background,
- a higher signal to noise ratio.

The threshold on the electron energy has to be kept low, 100 *keV*, to be sensitive to both the pp and ^7Be neutrinos. At low energy the detector medium has to be a gas because the recoiling electron track must have a minimum length (~ 3 *cm*) in order to be reconstructed. The electrons of the gas are the targets for the ν_e scattering.

The HELLAZ TPC has been firstly discussed in⁶⁾ and a Letter of Intent has been submitted last January. It concerns a 2000 *m*³ chamber filled with 7 tons of $\text{He} + \text{CH}_4$ (95/5). Such a gas density (3.5 *gr/l*) can be reached with different combination of pressure and temperature: 20*bar*/300*K*, 10*bar*/140*K*, 5*bar*/77*K*. A recent review of the project is given in⁷⁾.

In this paper I will discuss, instead, the project of a solar TPC filled with CF_4 at 1 *bar* pressure. CF_4 has at the same time a low atomic number and a high density

(3.7 *gr/l* at 1 *bar* and room temperature). The low atomic number minimizes the multiple scattering, allowing for a good track reconstruction, whereas the high density maximizes the number of target electrons. I will found my discussion on the results of the MUNU experiment⁸⁾⁹⁾¹⁰⁾.

MUNU was designed to study the $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ scattering with the antineutrinos from a nuclear reactor. The detector is running in the Bugey laboratory, at a distance

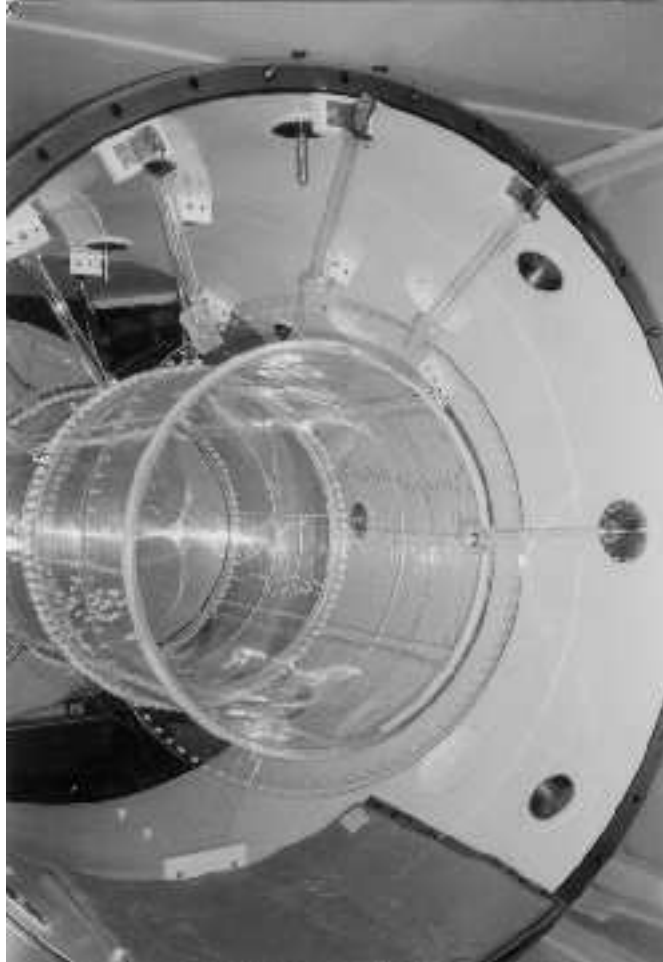


Figure 1: The TPC mounted inside the anti-Compton without the anode plane.

of 18m from the core of a 2800MWth reactor. It consists of a 1 m^3 TPC immersed into 10 m^3 of liquid scintillator working as anti-Compton (Fig.1). Since the anti-neutrino event rate is low it has been necessary to minimize all possible background sources and to construct each part of the detector from selected low radioactivity material.

The central detector is an acrylic vessel TPC, a cylinder of 90 *cm* inner diameter and 162 *cm* long, filled with CF_4 at 3 *bar* pressure. Acrylic is selected as construction material because of its low intrinsic radioactivity¹¹⁾.

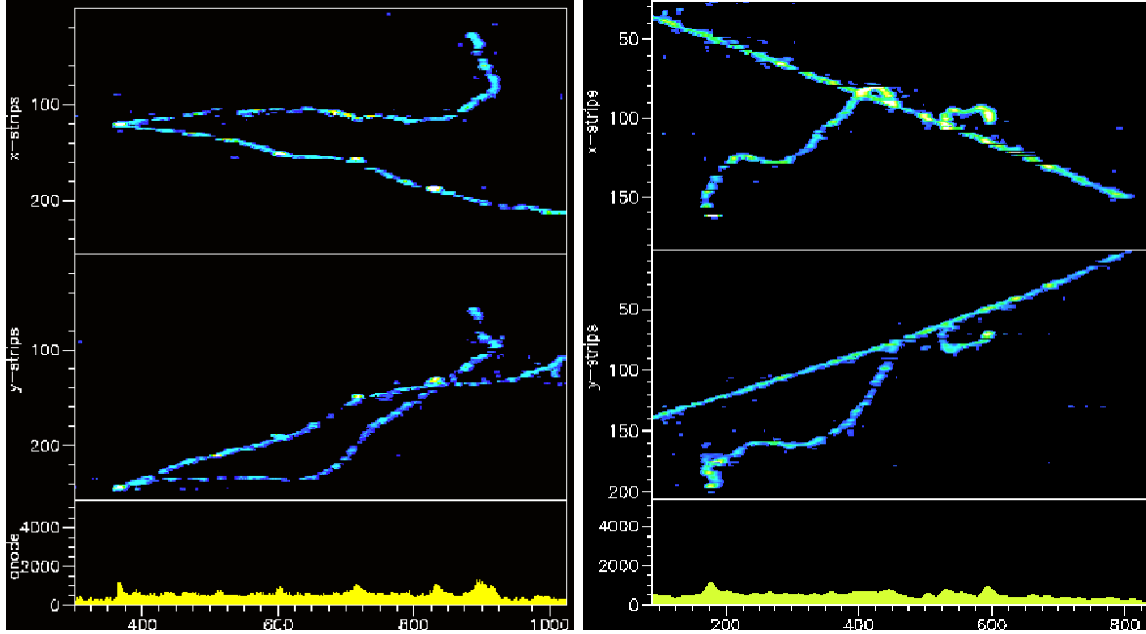


Figure 2: An e^+e^- event and a cosmic muon going through the TPC with the production of 2 deltas: vertical projection, horizontal projection and energy deposition as function of time. The binning is 3.5 mm for x and y and 80 ns for the time (i.e. 1.7 mm for z).

The acrylic TPC is mounted inside a stainless steel tank (3.8 m long and 2 m in diameter) filled with liquid scintillator. The liquid scintillator, 50 cm thick, serves to veto the cosmic muons and as anti-Compton detector. It is viewed by 48 hemispherical photomultipliers, 24 on each lid, of 20 cm diameter and made with low activity glass.

Outside the steel vessel there are a 8 cm thick boron loaded polyethylene shielding and a 15 cm thick lead shielding to absorb neutrons and gamma rays entering the detector from outside.

The MUNU detector is the first one able to see the event peak due to the $\bar{\nu}_e$ from a nuclear reactor and able to do the neutrino spectroscopy in the region below 1 MeV. As a matter of fact, it does exactly the same as what a solar neutrino TPC should do (the only difference is the flux at the detector site: the neutrino flux from the Sun is more than two orders of magnitude lower than the anti-neutrino flux from the reactor). As a consequence, it can be regarded as a low background prototype of a solar TPC. Clearly the detector is not optimized to work at 1 bar, many of the technical solutions we selected cannot be adopted in a much bigger detector and, finally, it is running in a place far different from a 'silent' underground laboratory. However the results it has provided on track reconstruction, energy resolution and background suppression can be regarded as a sound starting point for a solar neutrino TPC project.

Fig. 2 shows an e^+e^- event and a cosmic muon, whereas in fig. 3 there are two low energy electron events. The electron energy and angular resolution are such that

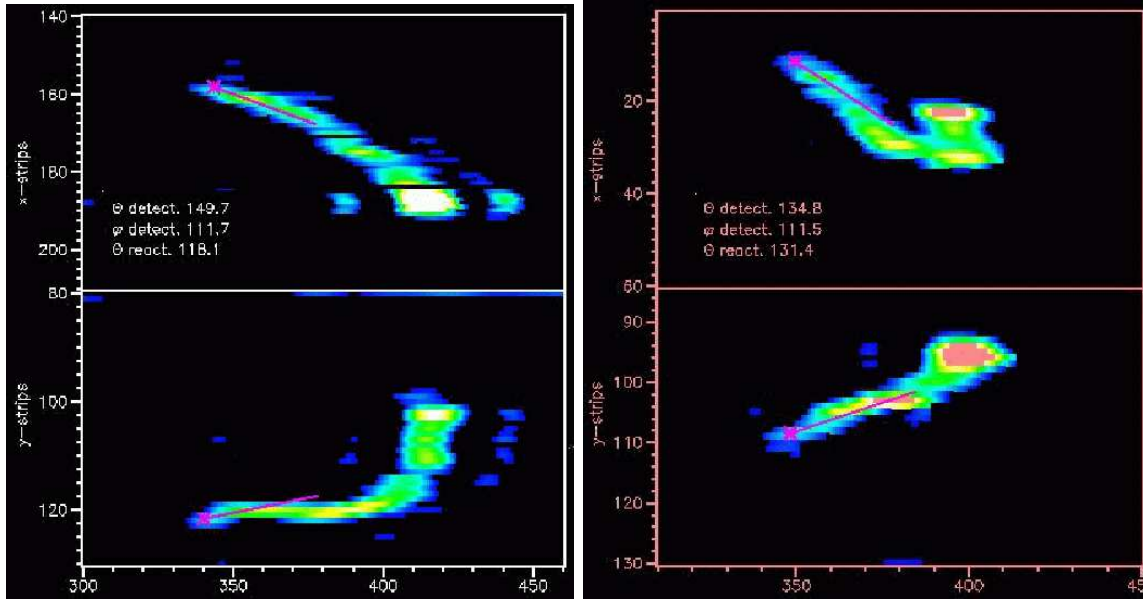


Figure 3: Low energy electrons of 590 keV and 460 keV energy (18 cm and 12 cm range, respectively).

it has been possible to reconstruct the ^{54}Mn photo-peak (γ energy=835 keV) with a σ of 220 keV by measuring the energy and the direction of the Compton electrons inside the TPC¹⁰). This is an encouraging results because it shows that the ^7Be neutrino peak (862 keV) could be reconstructed in a TPC filled with CF_4 even at 3 bar pressure and with a 300 keV threshold on the kinetic energy of the recoiling electron.

The background requires a more detailed discussion. The electron and α particle rates were at the beginning much higher than the predicted ones because of the ^{222}Rn emitted by the oxysorb through which the gas is going to remove Oxygen and water.

As a matter of fact, the Radon signature can be easily seen in our detector (fig. 4): an electron from the β decay of ^{214}Bi (end-point: 3.26 MeV) followed by the α decay of ^{214}Po (α energy: 7.8 MeV, half-life: 164 μs).

After having replaced the oxysorb and changed the TPC cathode, where the Radon daughters were collected, we reached an event rate over the 4π solid angle of 350 cpd (counts per day) and 50 cpd for electron kinetic energy above 300 keV and 800 keV, respectively. We remark that such rates, when divided by the 11.1 kg of the CF_4 mass, are very similar to the cpd/kg measured in Gran Sasso by low background Germanium detectors surrounded by Copper, Lead and with an anti-Radon shielding.

The active shielding, the scintillation light of CF_4 itself and the the possibility of defining a fiducial volume have been particularly helpful in reducing the background of the MUNU detector. I think that they are key features of the detector which must also be kept in the solar TPC.

However, in spite of its low value, the MUNU background is still too high for a

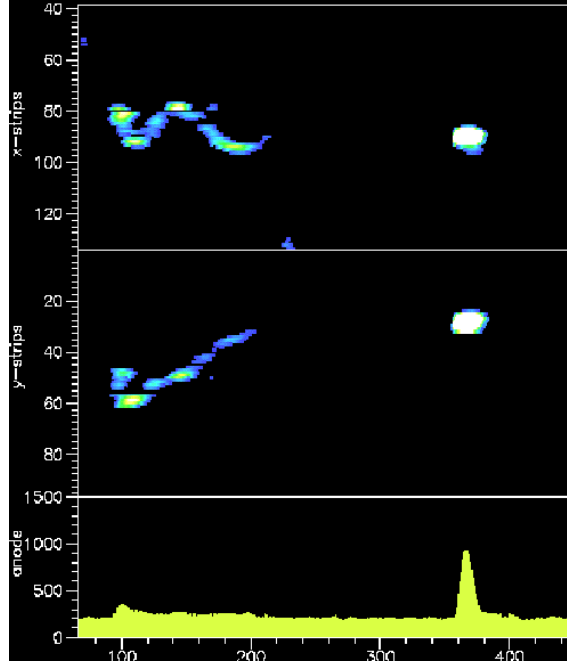


Figure 4: An electron- α event due to a $Bi - Po$ decay. The α can be easily identified because of the short track and the large energy deposition.

solar neutrino TPC. The minimum volume of such a TPC should be at least 200 m^3 (which corresponds to a mass of 0.74 ton of CF_4) for a count rate of about 1 solar event/day (half due to pp and half to 7Be neutrinos, assuming the Standard Solar Model neutrino flux and a 100 keV threshold on the electron kinetic energy). Fig. 5 shows the reconstructed energy spectrum of the pp and 7Be neutrinos interacting during 10 years inside a 200 m^3 TPC filled with CF_4 at 1 bar pressure. The electron energy resolution used in the simulation has been measured with a prototype TPC, whereas the angular resolution is given by Monte Carlo. It takes into account the multiple scattering of the recoiling electron and the diffusion of the ionization electrons along a drift distance of 5 m (with the initial 2 cm of the track used to fit the direction). The resolution at the 7Be peak is in agreement with the ${}^{54}Mn$ peak measurement made at 3 bars .

We remark that, thanks to the high density of CF_4 , we can have a reasonable target at atmospheric pressure and room temperature, and we point out that the existing liquid Argon TPC of the Icarus experiment has already a $\sim 200\text{ m}^3$ volume. With a solar neutrino signal of 1 event/day, assuming a 300 day data acquisition time, we can have a background of, at most, ~ 19 events/day within a $\pi\text{ sr}$ solid angle (this way the signal is higher than 4 times the background fluctuation).

To prove that this is reachable we need a count rate of, at most, 3 events/week above 100 keV in the MUNU TPC running at 1 bar pressure (for event we mean a single electron in the fiducial volume of the TPC without any energy deposition

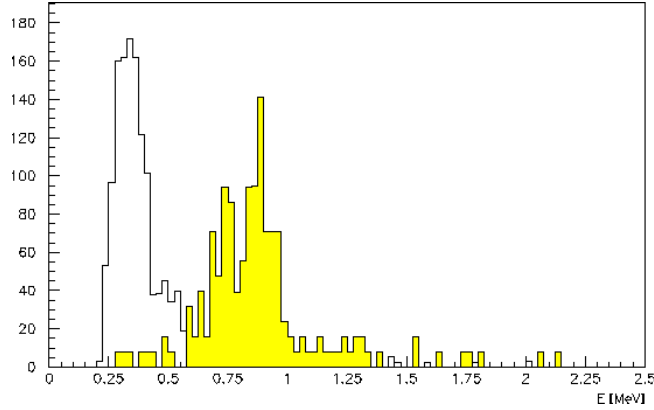


Figure 5: Simulation of the pp and ${}^7\text{Be}$ neutrino spectra in 10 years of data taking. Only the effects due to the gas are taken into account.

larger than 100 keV in the anti-Compton). Roughly speaking it is an improvement by 3 orders of magnitude as compared to what we have now in Bugey. In particular, the two following background sources need a detailed study:

- Radon: it is probably the most subtle background source. In MUNU, after having replaced the oxisorb filter, we have an activity of about 0.5 mBq/m^3 . The solar neutrino experiment is feasible only if the the Radon activity could be decreased to the $\mu\text{Bq/m}^3$ level. An activity lower than $0.5\text{ }\mu\text{Bq/m}^3$ has already been achieved for Nitrogen purified in the liquid phase¹²⁾. We have to study if a similar treatment were possible for CF_4 .
- ${}^{14}\text{C}$: it beta decays with the end-point at 156 keV (half-life:5730 years) and it is an extremely severe background source for the detection of pp neutrinos. In the atmosphere there are about 10^{-12} gr of ${}^{14}\text{C}$ per gr of ${}^{12}\text{C}$. Borexino has measured $1.8\cdot 10^{-18}\text{ gr/gr}$ of ${}^{14}\text{C}$ in liquid scintillator¹³⁾. Its content in CH_4 (used for the production of CF_4) is not known. For the pp neutrino detection it cannot be higher than $2\cdot 10^{-19}\text{ gr/gr}$. Such a content would produce 10 events/day in the 200 m^3 solar TPC (within a solid angle of $\pi\text{ sr}$) and 1.5 events/week in the MUNU TPC.

It is clear that the decisive factor in a solar neutrino experiment is the background and that the attainment of the required background can be proved only in an underground laboratory. Because of this I think that the next step towards a solar neutrino TPC should be the installation of a prototype in an underground laboratory as a counting test facility.

4. Summary

I described the two methods which are studied for the spectroscopy of the pp and ${}^7\text{Be}$ neutrinos from the Sun: absorption in a loaded liquid scintillator and elastic scattering in a TPC.

From the point of view of the physics the two approaches are complementary, since the charged current interaction is only sensitive to ν_e whereas the neutral current one is also sensitive to ν_μ and ν_τ .

Background suppression is probably the most difficult task for both methods. I think that the richer information provided by a TPC might be a decisive factor to achieve the required background. On the other hand a liquid scintillator detector is clearly a much 'easier' detector than a TPC.

The capability of suppressing the background to the required level can only be proven for both methods by a prototype measuring in an underground laboratory.

5. Acknowledgments

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6. References

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